OCCASIONAL SCIENTIFIC PAPERS OF THE WESTWOOD ASTROPHYSICAL OBSERVATORY. NUMBER 1, 2, 3. LUNAR AND TERRESTRIAL ALBEDOES; THE LUMINIFEROUS ETHER; THE RADIANT PROPERTIES OF THE EARTH FROM THE STANDPOINT OF ATMOSPHERIC THERMODYNAMICS

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Occasional Scientific Papers
OF THE
Westwood Astrophysical Observatory
NUMBER I.

LUNAR AND TERRESTRIAL ALBEDOES

By
FRANK W. VERY

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HISTORICAL NOTE

Founded in 1906, the Westwood Astrophysical Observatory owes its inception to aid from Percival Lowell. In beginning a special series of its publications, the writer wishes to place on record his indebtedness to the warm sympathy and encouragement of a faithful friend. Himself an ardent lover of freedom, Dr. Lowell never interfered with the writer's free and independent ordering of the researches conducted at Westwood, but with a rare disinterestedness he placed at his disposal numerous spectrograms taken at the Lowell Observatory by the skilful hands of Dr. V. M. Slipher for measurement with apparatus of the writer's design. Nevertheless, the gain was mutual, for the results throw unexpected light on some of Lowell's own researches and demonstrate that complete independence in respect to control and motives of action is not incompatible with a consistent working together for a common end.

Lowell had been greatly interested in the research which forms the subject of the present communication, with its obvious bearing on the problem of planetary temperature. In his "Temperature of Mars," he had adopted 0.75 for the albedo of a half clouded earth, and I, in my "Greenhouse Theory and Planetary Temperature," had taken 0.70 for the same datum, differing but little from the value now found for the geometrical albedo of the earth, which is 0.72.

Let me also place on record as a result of my intimate association with him, my recognition of the fact that his theories were based on an elaborate accumulation of unsurpassed evidence, that he was always open-minded to new evidence, and that, while presenting some revolutionary new conceptions, he did not hesitate to modify his own ideas when convinced that they could be improved. It is this willingness to revise that constitutes the true man of science. That there was very little for him to change as his researches progressed, is a testimony to Lowell's thoroughness and to his deep insight into nature's mysteries.

With gratitude to God for the gift of a friend—generous, thoughtful for others, and noble in his ideals, keenly critical, but kindly appreciative, learned, but modest—

I dedicate these researches

To the Memory of
Percival Lowell

THE WESTWOOD ASTROPHYSICAL OBSERVATORY

THE WESTWOOD ASTROPHYSICAL OBSERVATORY is situated in Westwood, Massachusetts. Its approximate position and altitude (derived from the topographical map of the United States Geological Survey) are

Latitude = 42° 12′ 58″ North.
Longitude = 71° 11′ 58″ West.
Altitude = 190 feet above sea level.

Its publications hitherto have been in current scientific periodicals, especially, *Lowell Observatory Bulletin, American Journal of Science, Astrophysical Journal, Science, Astronomische Nachrichten,* and *Bulletin Astronomique.*

The Observatory possesses special instruments for the study of solar radiation and atmospheric transmission, for delicate heat measurements, the utilization of solar radiation and study of the "greenhouse" effect, photometry, spectral line and band comparator, etc. For several years it had the use of a fine silver-on-glass concave mirror of 12 inches aperture and 10 feet focal length, which was loaned by its maker, Dr. J. A. Brashear. The mirror was used in researches on the transmission of terrestrial radiation by the aqueous vapor of the atmosphere.

Special researches are being actively prosecuted on atmospheric transmission and the solar constant, quantitative measurements of the intensity of spectral lines, planetary atmospheres and temperatures, greenhouse theory, contributions to the theory of nebulæ and novæ, measurements of the earth's albedo and of that of the moon for all parts of the visible spectrum. The latter researches form the subject of the present communication.

LUNAR AND TERRESTRIAL ALBEDOES

Introduction.

THE word *albedo* (derived from the Latin *albus*, white) has been used by astronomers to designate the fraction of the sun's luminous rays reflected by a planet at full phase, allowance being made for the distances of the planet from sun and earth and for the dimensions of the reflecting body. If the planet were a smooth sphere with perfect specular reflection, it would be itself invisible, but would present within the diminutive limits of its disk a complete picture of the surrounding heavens, distorted by spherical aberration, but otherwise exact; and within this image the reflection of the sun would surpass in brilliancy all other objects, shining like a star at a point on the planet's disk distant from the center by the radius of the disk multiplied by the cosine of half the elongation of the planet from the sun. But whatever specular surfaces there may be on the planets of our solar system, they are of too limited extent to be recognized as such; and the planetary reflection of light is to be classed under the head of a generally diffusive one, though not necessarily an equable one in all directions; and in fact there are diversities in the distribution of the reflected light to different parts of the sphere which must be considered in getting the phase-curve of the illumination, and which are not entirely without influence even if we confine our attention to the reflection sent earthward at full phase, while they are vital to the determination of the complete reflection to the sphere.

Since all of the planets, except possibly some of the smaller asteroids, are spheroidal bodies, it is not necessary for purposes of intercomparison to refer their albedoes to the standard specific reflectivity of a flat surface; but it *is* desirable to distinguish clearly between the only thing which is certainly measurable in most cases,—which is (1) the geometrical albedo at full phase, or the amount of light sent earthwards at the planet's full phase, compared with that which would be sent by a sphere of the same size and at the same distance, which possesses perfect diffusive reflectivity;—and (2) that integration of the reflection to the entire sphere, or the *spherical* albedo, whose determination requires a knowledge of the phase-law. This law is very imperfectly known, except in the case of the moon, and hence there are rival hypotheses which give more than one kind of "spherical" albedo. There is even a diversity of usage in regard to what shall be called the "geometrical" albedo, although there need be no discrepancies in the facts of observation on which it is based. A very few words will suffice to make the fundamental distinctions plain as to their general principles; but the remoter consequences of the acceptance of the diverse points of view lead to discussions of some complexity whose complete unfolding can not be exhibited in the limits of this paper, but enough will be presented to give an intelligible conception of the subject.

If we measure the amount of light received by the eye from the full moon, that is to say, if we find the reflection of sunlight by a spheroidal surface to a point (since the pupil of the eye is virtually a point), we shall get the same value whether the moon is near the horizon or in the zenith (after correcting for the absorption by the earth's atmosphere); and it seems natural to take this constant light-quantity as the basis of *the geometrical albedo referred to a definite point in space*, comparing it with the quantity of light which would be given if the whole sky were filled with moons of perfectly diffusive reflecting quality, and viewed by turning the eye progressively to all parts of the sky and summing the successive impressions. This geometrical ratio of the *reflection to a point* compared with the perfectly diffuse reflection at that point from an ideal body of the same size and in the same situation, is the one considered in this paper and is what is meant by the geometrical albedo.

But if, instead of this, we take the *illumination of an extended surface* by the hypothetical sky full of moons, it is necessary to take into account the diminution of superficial illumination from those rays which are at low angles to the surface, and even supposing an absence of atmosphere, the *surface* illumination produced by a sky full of moons will only be half as great as the sum of the illuminations supposing each moon to be successively transported to the zenith. Thus the "surface illumination" is one half of the geometrical albedo.

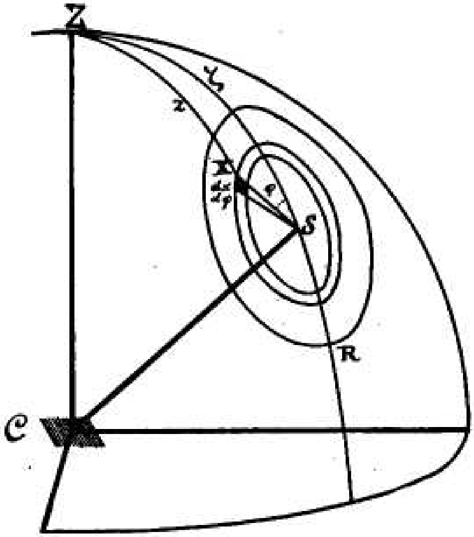

FIGURE 1

Lambert showed in his "*Photometria*" (*cap.* II.) that if we seek the illuminating power (L) of a circular luminary of radius $SR = r$ (Fig. 1), whose center is at any point (S) of zenith-distance $SZ = \zeta$, upon a surface at C, we may obtain L by summing a series of annuli concentric with S and of radius $SX = x$, where, if an element $(dx, d\varphi)$ of the annulus is at the angle $ZSX = \varphi$ from the vertical through S, the area of the element is $dx \cdot d\varphi \sin x$. Hence

$$L = \int\int \sin x \cos \zeta \, d\varphi \, dx,$$

since the illumination of the surface at C varies in proportion to $\cos \zeta$.

By spherical trigonometry, if z is the zenith-distance of any point X on the annulus,

$$\cos z = \cos \zeta \cos x + \sin \zeta \sin x \cos \varphi,$$

and

$$L = \int\!\!\int dx \cdot d\varphi \sin x \,[\cos \zeta \cos x + \sin \zeta \sin x \cos \varphi]\,.$$

A first integration relatively to φ between $\varphi = 0°$ and $\varphi = 360°$, or 2π, gives

$$L = \int dx \sin x \cdot 2\pi \cdot \cos \zeta \cos x.$$

Integrating this with respect to x from $x = 0°$ to $x = r°$,

$$L = 2\pi \cos \zeta \int \sin x \cos x \, dx$$

$$= 2\pi \cos \zeta \left(\frac{1 - \cos 2r}{4}\right) = \pi \cdot \cos \zeta \cdot \sin^2 r.$$

This gives for the illuminating power *(L)* of the moon at the zenith to that of a sky full of moons *(L′)* upon an extended surface at *C*, as a first approximation,

$$\begin{aligned} L : L' &= \pi \cos 0° \;(\sin^2 15' \, 33'') \;:\; \pi \cos 0° \;(\sin^2 90°) \\ &= 1 \;:\; 48{,}875. \end{aligned}$$

But if we consider the luminous effect upon a point, such as the eye, or the heating effect upon the bulb of a thermometer which may likewise be taken as a point, instead of that communicated to an extended surface, then, neglecting atmospheric absorption, it is necessary to find the ratio of illuminations by taking the ratio of the area of the apparent lunar disk to the hemispherical sky area, a ratio which is half as great as the one just given. For a disk as small as that of a planet, the area may be taken $= \pi \sin^2 \varrho \cdot r^2$, where ϱ is the angular value of the radius of the disk and r is the distance of the planet. Comparing this with the area of the hemisphere, $2\pi r^2$, the latter exceeds the former in the ratio, $2 : \sin^2 \varrho$, which, for the moon's semi-diameter, $\varrho = 15' \, 33''$, gives for the ratio of the light reflected to a point from the two sources,

$$97{,}750 \;:\; 1$$

with a similar degree of approximation to the preceding value.